

The National Polar-orbiting Operational Environmental Satellite System – Restructured Capabilities for Operational Ocean Remote Sensing

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Abstract—The tri-agency Integrated Program Office (IPO) continues to manage the development, acquisition, and execution of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). As directed by its acquisition decision authority in 2006, the NPOESS Program restructured its acquisition baseline with an emphasis on reducing complexity and ensuring continuity of observations presently delivered by the two operational systems NPOESS will replace – the Polar-orbiting Operational Environmental Satellite (POES) and the Defense Meteorological Satellite Program (DMSP). Ocean observations continue to comprise nearly one-fourth of the 38 user-validated data requirements levied on the system and are drivers of the design and implementation strategy for two principal sensors: the Visible Infrared Imager Radiometer Suite (VIIRS) and the Microwave Imager-Sounder (MIS). The NPOESS Preparatory Project (NPP) will deliver a subset of these NPOESS ocean observations for demonstration and risk reduction after its planned launch in 2010. Recent performance assessments indicate that the restructured NPOESS will continue to deliver improved operational capabilities and satisfy the critical civil and national security needs for space-based ocean observations.

I. INTRODUCTION

The Integrated Program Office (IPO), a tri-agency organization under the sponsorship of the Departments of Commerce (DOC) and Defense (DoD) and the National Aeronautics and Space Administration (NASA), manages the ongoing acquisition of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). Commissioned by Presidential directive [1], the system is designed to provide space-based observations of the ocean, land, atmosphere, and space environments and will deliver resultant data products to civilian and military users around the globe. When it becomes operational early in the next decade, NPOESS will provide the continuity, quality, and latency of data deliveries necessary to satisfy the operational threshold requirements of DOC and DoD and will meet or exceed heritage performance

capabilities that have been delivered for over 45 years by the programs and combined series of satellites NPOESS will replace—the National Oceanic and Atmospheric Administration (NOAA) Polar-orbiting Operational Environmental Satellite (POES) and the DoD Defense Meteorological Satellite Program (DMSP). The current space segments of DMSP and POES are likely to support DOC and DoD mission requirements, with high confidence, through 2009 (POES) and 2016 (DMSP). An Initial Joint Polar System (IJPS) satellite (NOAA-N'), a joint venture of DOC and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), is planned to fill the gap between the last POES satellite and the first operational launch of NPOESS.

The initial set of operational requirements for NPOESS were derived from source DoD and DOC documents [2, 3, 4] as updated by current DMSP and POES capabilities. Since this initial set included requirements based upon the known implementation of the current DMSP and POES programs, the IPO enlisted the user community to refine these requirements several times during the concept development phase of the program to eliminate implementation-specific concepts and to enhance the requirements based upon known state-of-the-science and emerging needs. In January of 2002, the Joint Requirements Oversight Council for NPOESS reviewed and approved the Integrated Operational Requirements Document, Version II (IORD-II) which established the requirements base [5] for the competitive selection of the NPOESS development contractor in August of 2002. The IPO subsequently awarded the contract to Northrop Grumman Space Technology (NGST) who, along with its ground systems subcontractor, Raytheon Intelligence and Information Systems, is responsible for developing, integrating, deploying, and operating the NPOESS system to meet the validated requirements over the operational life of the program. These responsibilities include

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command and control of the NPOESS satellites, data availability and processing at designated operational prediction centers to produce Environmental Data Records (EDRs), and delivery of these EDRs and other data records via each applicable user interface. NPOESS is accountable for total system performance as measured by the quality and latency of EDRs as delivered to the users. Each user agency determines if its unique customer base requires any “value added” products and provides the supporting infrastructure necessary to produce and deliver the supplemental products.

The initial space demonstration phase of NPOESS, the NPOESS Preparatory Project (NPP), is scheduled for launch in 2010. One of the five sensors manifested on NPP—the Visible Infrared Imager Radiometer Suite (VIIRS)—represents one of two NPOESS instruments with critical ocean observation applications. The supporting vendors have completed fabrication of the NPP spacecraft and all of the NPP sensors. The spacecraft and sensors are presently undergoing intensive environmental testing and integration.

II. NPOESS PROGRAM RESTRUCTURE

In June of 2006 the Under Secretary of Defense for Acquisition, Technology, and Logistics, acting in his capacity as the acquisition decision authority for the NPOESS Program, directed a restructuring of the system acquisition baseline. The purpose for this action was to respond to ongoing challenges in system development and testing by aligning the Engineering and Manufacturing Development phase of the program with the projected budget profile and to certify the NPOESS acquisition strategy. The restructure guidance provided in the governing Acquisition Decision Memorandum (ADM) [6] provides for operational support well into the 2023 timeframe while modifying the NPOESS architecture at its full operational capability. It delivers continuity of existing operational programs, constellation management flexibility, and best capability within cost while keeping growth potential to achieve the original capability envisioned for NPOESS.

The ADM eliminated the mid-morning orbit, described as the 2130 Local Time of Ascending Node (LTAN), from the NPOESS system architecture in favor of joint reliance on data from the EUMETSAT MetOp series of satellites, which become a principal data source in this orbit along with DMSP at the approximate time of the first NPOESS launch.

With the NPOESS presence focused on the early morning (1730 LTAN) and afternoon (1330 LTAN) the total number of satellites was adjusted from six to four.

Selected sensors deemed not critical to the core NPOESS operational mission were removed from satellite manifests. Among these sensors was the radar altimeter (ALT) originally planned for the second in the series of NPOESS satellites in order to deliver two ocean-related EDRs—Ocean Wave Characteristics and Sea Surface Height. Despite the removal of these sensors, the ADM also directed that NPOESS maintain sufficient weight, power, interface, and real estate margins on the appropriate satellites so that the affected

sensors could be reinstated without prohibitive redesign to the system. In fact, funding has been added and plans are in place to remanifest two of the affected sensors—the Ozone Mapping and Profiling Suite (OMPS) Limb Profiler (on NPP only) and the Total Solar Irradiance Sensor (TSIS).

A new passive microwave polarimetric sensor was commissioned to replace the previously planned Conical Microwave Imager Sounder (CMIS) which was deemed to have excessive development risk. The new sensor, tentatively named the Microwave Imager Sounder (MIS), will be manifested on the second NPOESS satellite. MIS is in its early requirements definition and risk reduction phase and may have inherent capability to produce six ocean-related EDRs—Imagery, Sea Surface Temperature (SST), Ice Surface Temperature, Sea Surface Winds, Ocean Surface Wind Stress, and Sea Ice Characterization.

Data products applicable to the ocean observation mission area comprise nine of the total of 38 user-validated requirements for geophysical measurements to be made by NPOESS sensors. They are based on current uses and applications of satellite ocean observations (itemized in Table I), existing capabilities of operational and research satellites with ocean observation capabilities such as the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA Terra and Aqua satellites, and projected needs for improved capabilities to support emerging operations in coastal and open ocean regions.

TABLE I
APPLICATIONS OF NPOESS OCEAN OBSERVATIONS

OCEAN OBSERVATIONS	APPLICATION EXAMPLES
Images of Surface Features	Location of currents, fronts, eddies Fisheries management Ship detection Oil rig stability management
Surface Temperature	Location of currents, fronts, eddies Fisheries management Marine weather forecasts Climate monitoring Sea ice persistence Surface and subsurface navigation
Water Color	Biological productivity Fisheries management Harmful algal bloom detection Pollution detection and monitoring Coastal erosion and runoff Diver and submerged object detection
Surface Wind Speed	High seas detection and forecasts Severe weather forecasts Biological productivity zones Ship routing Surface effluent dispersion
Surface Wind Direction ¹	Severe weather forecasts Biological productivity zones Ship routing Surface effluent dispersion
Sea Surface Height ²	Ocean currents and eddies Sea level change analysis Climate change forecasts Severe weather forecasts
Ocean Wave Height ²	Ship routing Platform design Coastal erosion

¹Dependent on final MIS performance which remains to be specified

²Requires remanifesting of radar altimeter to provide these observations and additional EDRs

A. System Attributes

The restructured NPOESS system architecture retains nearly all of the unique aspects that allow users to receive space-based observations with a quality and latency not achievable from the heritage operational programs. It enables users to receive timely data products as a direct or tailored product from the designated operational prediction centers, as real-time data products received via direct downlink broadcast, or as raw or processed data from the DOC-sponsored archive.

NPOESS Stored Mission Data (SMD) include all sensor and spacecraft data collected by each satellite and transmitted via a Ka-band link to any of 15 globally distributed ground receptor sites. SMD are then relayed via a ground-based fiber-optic network to the designated operational prediction centers for processing. The processed EDRs are available for exploitation directly or as input to follow-on processing by the operational prediction centers for the provision of tailored products to end users. The system is designed to complete the processing and make available for delivery 75 percent of EDRs within 15 minutes of their time of observation (daily average) and 95 percent of EDRs within 28 minutes, representing performance that is three-fold faster than the most stringent IORD-II threshold requirements for data latency.

The system will also provide continuous X-band High Rate Data (HRD) and L-band Low Rate Data (LRD) direct broadcasts to transmit data to field terminals equipped with applicable receiving and processing software. The HRD broadcast has sufficient bandwidth (20 Mbps) to allow all observation data to be transmitted at their full resolution. The LRD broadcast will offer a prioritized subset of data products at a lower data rate, the contents of which can be tailored as the need arises. The NPOESS Program plans to deliver descriptions of the necessary hardware configuration and associated software to the public domain to support field terminal development and world-wide exploitation of the data products.

B. Ocean Sensors

The current manifests for NPOESS satellites are provided in Table II. The operational concept consists of two spacecraft in sun-synchronous orbits (98.7 degree inclination) with 1730 and 1330 LTAN. The instrument manifests vary between satellites based on data refresh requirements, specific orbital characteristics such as the sun's terminator, instrument field-of-view considerations, and sensor development maturity (in the case of MIS).

The NPP satellite is considered a risk reduction mission for NPOESS and will be used to verify the system's command, control, communications, and ground processing elements as well as validate algorithms supporting sensor data records (SDRs) and EDRs. NPP will also deliver raw data to be used by NASA to provide continuity of earth observations supporting climate research and provide a bridge between the NASA Earth Observing System and the first NPOESS satellite. The NPP manifest includes the VIIRS sensor and its associated ocean observation capabilities.

TABLE II
NPOESS SENSOR MANIFESTS

NPP	C1	C2	C3	C4
VIIRS	VIIRS	VIIRS	VIIRS	VIIRS
CrIS	CrIS	MIS	MIS	MIS
ATMS	ATMS	SARR	CrIS	SARR
OMPS	OMPS	SARP	ATMS	SARP
CERES	CERES	A-DCS	OMPS	A-DCS
	TSIS		SEM-N	
	SEM-N		SARR	
	SARR		SARP	
	SARP		A-DCS	
	A-DCS			

Sensor acronyms not otherwise defined in text:
 CrIS – Cross-track Infrared Sounder
 ATMS – Advanced Technology Microwave Sounder
 CERES – Clouds and the Earth's Radiant Energy System
 SEM-N – Space Environment Monitor – Next Generation

The first operational NPOESS satellite (C1) is planned for launch in 2013 into the 1330 LTAN orbit. Its manifest includes the VIIRS sensor. Improvements and “lessons learned” from NPP such as refinements to algorithms, calibration procedures, and validation techniques will be adopted prior to launch. The second NPOESS satellite (C2) is nominally planned for launch in 2016 into the 1730 LTAN orbit. Both VIIRS and MIS—the two primary ocean observation sensors—are included in its manifest. The third (C3) and fourth (C4) NPOESS satellites are nominally planned for launch in 2020 and 2022 but are contingent on incremental operational assessments that will occur after each preceding launch.

1) Visible Infrared Imager Radiometer Suite (VIIRS)

VIIRS will combine the radiometric accuracy of the POES Advanced Very High Resolution Radiometer (AVHRR) with the high spatial resolution of the DMSP Operational Linescan System (OLS) [7]. The VIIRS spectral bands are represented by 22 individual channels across the visible, near infrared, and infrared electromagnetic spectrum. They include five fine resolution channels, 16 moderate resolution channels, and a panchromatic day/night band. The fine resolution channels have nearly constant horizontal sampling intervals from nadir viewing to the edge of its ~3000 km swath width, with resolution at nadir of better than 400 m (the moderate resolution channels are approximately twice this horizontal interval). VIIRS will deliver observations of sea surface temperature, ocean color and chlorophyll, sea ice, atmospheric aerosols, cloud cover, surface albedo, and snow cover. Performance at the sensor level is expected to be comparable to MODIS [8], and as such represents a noteworthy transition of technology from research and development to operations.

2) Microwave Imager Sounder (MIS)

Although the sensor design for MIS is still under development, the technological foundation upon which this sensor will be based is well known. Inherent MIS capabilities

will combine much of the microwave imaging and atmospheric sounding capabilities of the Special Sensor Microwave Imager Sounder (SSMIS) on the most recent DMSP satellites with the passive, polarimetric capabilities of the Coriolis-WindSat mission launched under Navy, IPO, and Air Force Space Test Program sponsorship in January of 2003. Full polarization for selected channels could be used to passively derive ocean surface wind vectors similarly to the WindSat wind vector demonstration. Other EDRs for which the MIS sensor technology will potentially support include all-weather sea surface temperature, soil moisture, sea ice characterization, precipitation, snow water equivalent, cloud liquid water, cloud base height, and atmospheric vertical profiles of temperature and moisture.

In August of 2007 the NPOESS Program requirements sponsors represented by the Senior Users Advisory Group developed and delivered guidance to NPOESS on desired product priorities to assist in early MIS requirements development [9]. The highest priorities, not surprisingly, included maintenance of at least heritage performance for the core radiometry channels between 10 and 89 GHz needed to support key system requirements, followed by the provision of vertical profile sounding channels and all-weather surface (land/sea) temperature measurement capability.

The IPO announced in May of 2008 the selection of the Naval Research Laboratory (NRL) to develop the first in the series of MIS instruments. The NRL plans to move production of additional flight units for subsequent NPOESS launches to an industry partner, should this prove more cost-effective.

3) Other Sensors of Interest

The Search and Rescue Repeater (SARR), Search and Rescue Processor (SARP), and ARGOS Data Collection System (A-DCS) instruments will also be manifested on each NPOESS satellite. Although they do not make earth observations or deliver EDRs, they have applicability to the ocean user community. SARR and SARP service the international Search and Rescue Satellite Aided Tracking System (SARSAT) by receiving distress signals from emergency position-indicating radio beacons (EPIRBs) on the standard distress frequency of 406 MHz and retransmitting them to local user terminals to facilitate action by appropriate government agencies. The A-DCS instrument provides two-way relay of meteorological, oceanographic, and other data from and to in-situ, surface-based buoys and related data collection platforms.

C. Ocean Data Products

EDRs represent the end product of the NPOESS system. They are produced at each of the designated numerical prediction centers and represent raw data that have been calibrated and geolocated into SDRs and then processed using science-based algorithms and supporting ancillary data into desired geophysical parameters. The number and identity of EDRs vary between satellites primarily due to the sensor manifest. Fig. 1 illustrates the sensors and the 24 associated

EDRs to be delivered by the system from the NPP satellite [10]. Products for which NPOESS will process and deliver raw or sensor data for further EDR development by other government agencies are not counted in the EDR totals and are represented by a yellow perimeter surrounding the associated mission area symbol. As described in the key in the upper left-hand corner in the figure, EDRs that have direct applicability to the ocean observation mission area have a highlighted mark in the lower right corner of each symbol.

Figs. 2 and 3 provide a similar representation of EDRs from the NPOESS C1 and C2 satellites. Note the introduction of the MIS sensor on C2 and the additional ocean EDRs that are delivered as a result.

Fig. 4 illustrates the planned sensor manifest and EDRs delivered by the NPOESS C3 satellite. Although its launch would occur beyond the Engineering and Manufacturing Development phase of the NPOESS Program, it is included here since it illustrates the complete set of 38 EDRs to be delivered by the restructured program.

The NPOESS C4 satellite will include the same sensor manifest and deliver EDRs analogous to that shown for C2 in Fig. 3.

III. PERFORMANCE ESTIMATES

The maturity of VIIRS development and the availability of test data emerging from ongoing environmental testing permits early insight into performance estimates for NPP-era ocean products. This is not the case for MIS, which has not reached a level of definition and development maturity to support provision of performance estimates (recognizing that heritage performance as delivered by DMSP SSMIS represents the minimum acceptable performance requirements for MIS). In the case of VIIRS, we emphasize SST and Ocean Color/Chlorophyll (OC/C) which are the two primary ocean-related EDRs delivered by this sensor.

A. Sea Surface Temperature (SST)

Based upon analyses of completed sensor and algorithm testing and an assessment of remaining performance risks, the system has the intrinsic capability to satisfy established performance specifications for the SST EDR [11]. This includes 0.1 K Measurement Accuracy and 0.5 K Measurement Uncertainty attributes for both the surface boundary layer (skin) and upper 1 m layer (bulk) SST, and a horizontal cell size of 400 m at nadir. The science algorithm employed is similar to the heritage algorithm used to exploit ocean surface observations from the AVHRR and MODIS sensors. Certain sensor effects (near-field response; cross-talk; sensor stability; absolute radiometric calibration uncertainty) need to be fully characterized during remaining sensor testing and appropriately mitigated. Additional algorithm verification will be conducted to ensure adequate performance of the supporting VIIRS Cloud Mask and particularly sensitive performance areas including uniform, low-level, and relatively warm water cloud detection.

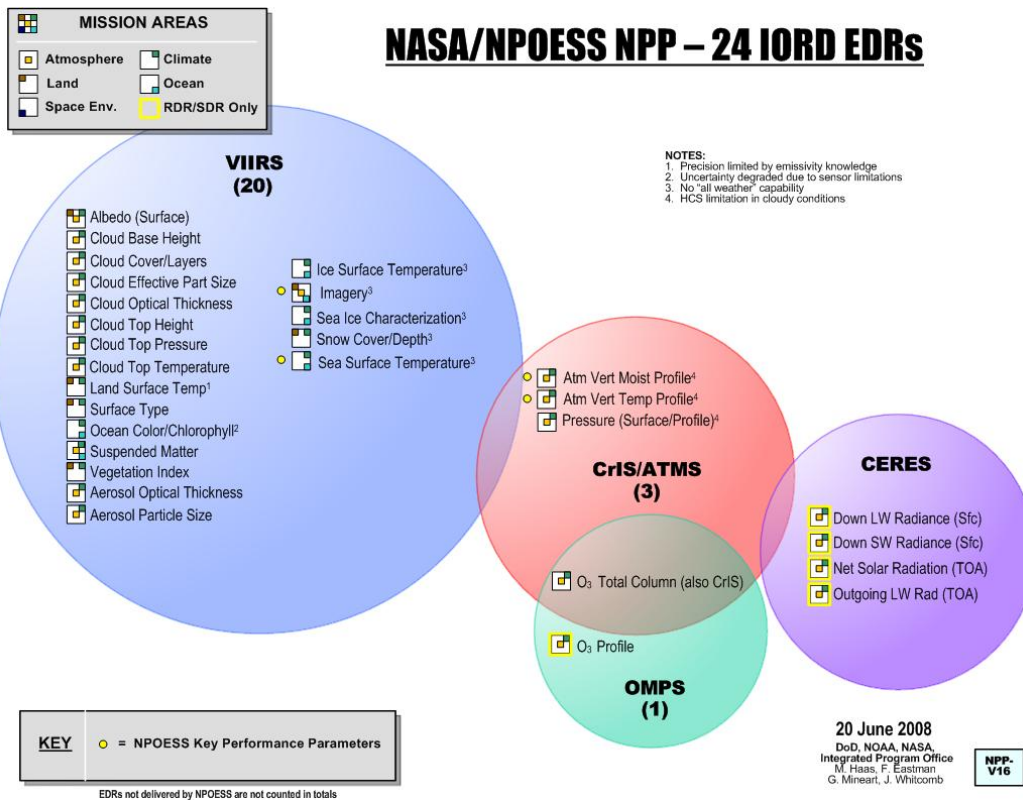


Fig. 1. Projected availability of EDRs by sensor from NPP

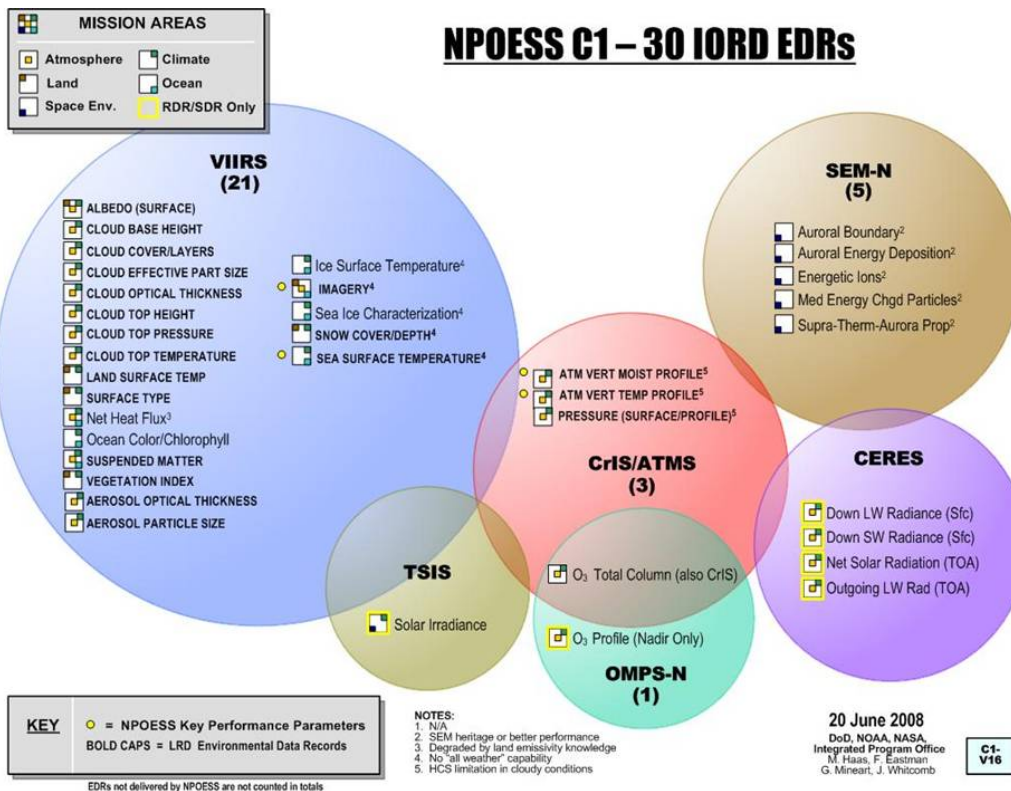


Fig. 2. Projected availability of EDRs by sensor from NPOESS C1

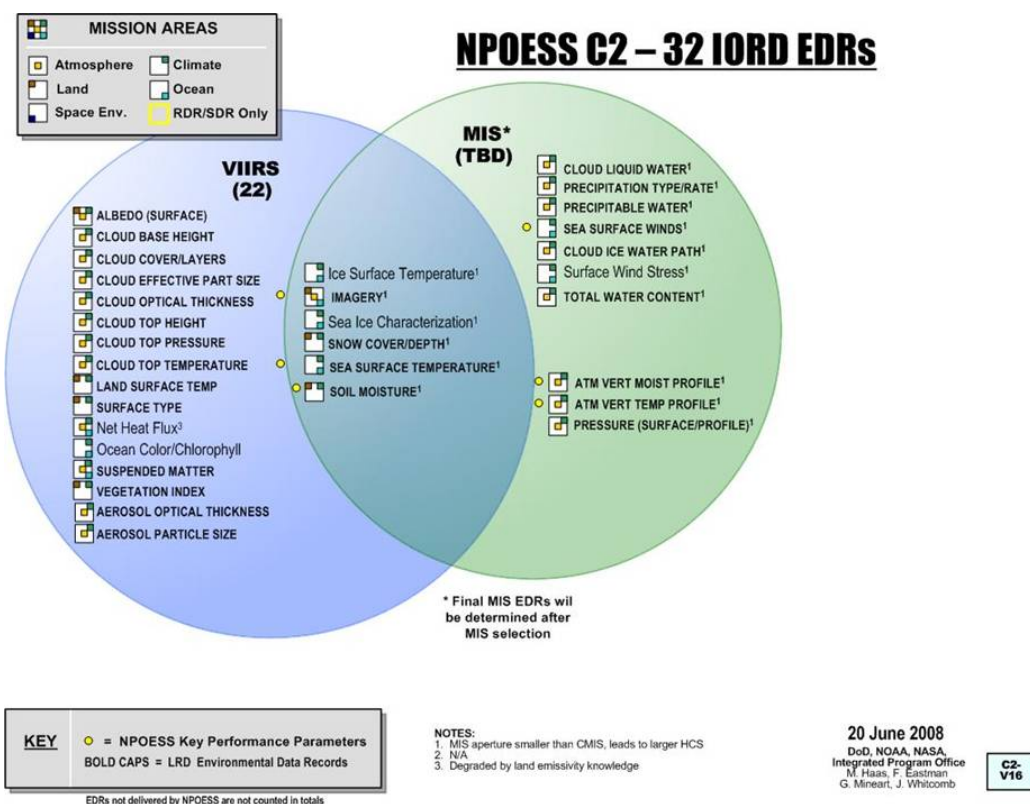


Fig. 3. Projected availability of EDRs by sensor from NPOESS C2

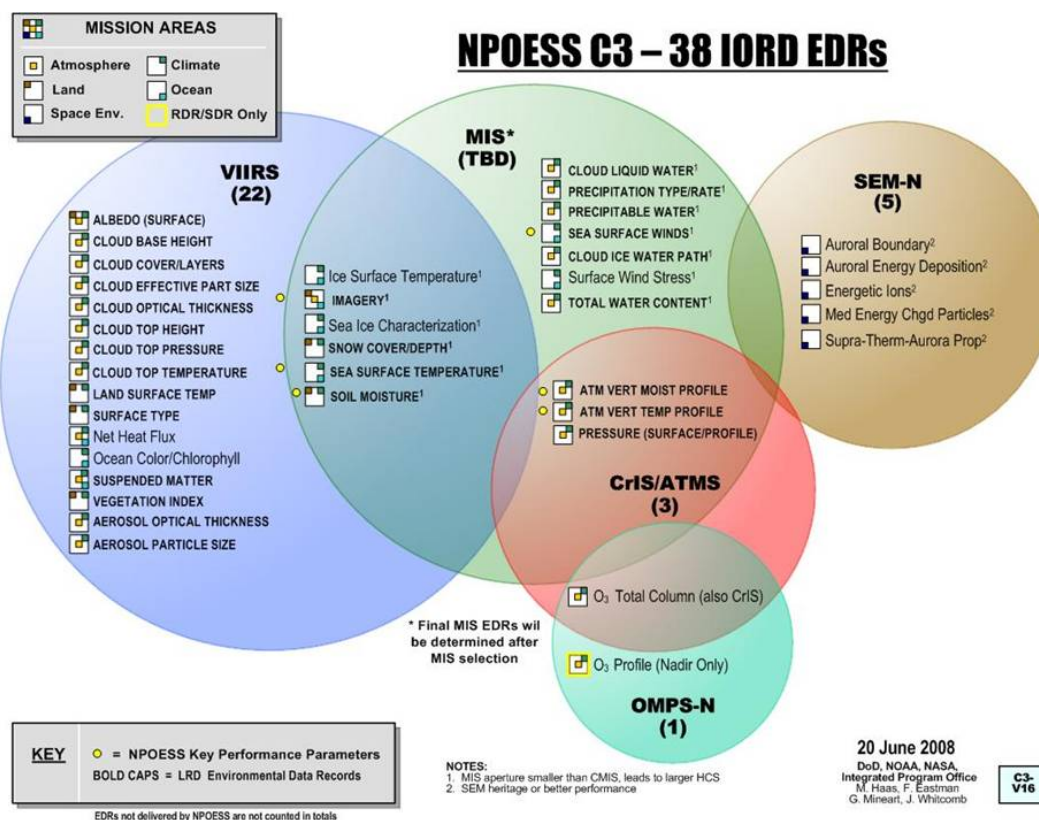


Fig. 4. Projected availability of EDRs by sensor from NPOESS C3

Fig. 5 provides an example test scene of Bulk SST resulting from NGST algorithm chain testing [12] using geophysically realistic test data. The results reveal acceptable performance and reasonable SST values for the selected scene.

B. Ocean Color/Chlorophyll (OC/C)

The normalized water-leaving radiance (nLw) is the fundamental component of the OC/C EDR. Ocean color represents the spectrum of nLw at each wavelength from which the concentration of phytoplankton pigment chlorophyll and optical properties of surface water can be derived. Since nLw represents only a small fraction of the total measurable radiance at the top of the atmosphere, with the majority of the signal coming from a variety of atmospheric effects that must be accurately mitigated, the OC/C EDR is critically dependent on the radiometric stability and signal-to-noise in the seven supporting VIIRS channels distributed below $0.865 \mu\text{m}$. Specified performance for OC/C on NPOESS is particularly challenging when compared to levels of performance achieved using dedicated science sensors such as MODIS. Examples of specified performance attributes of key interest include accuracy and precision for ocean color, with values of $0.1 \text{ W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$ or 10% (whichever is greater) and $0.05 \text{ W m}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$ or 5% (whichever is greater), respectively.

Levels of optical cross-talk observed in the Integrated Filter Assembly (IFA) during NPP sensor testing are sufficient to increase the signal uncertainty in the affected VIIRS channels to the point that they impact the performance of the OC/C EDR. As a result, the accuracy and precision of the OC/C EDR that will be delivered by NPP is expected to be less than that achievable in MODIS science products and will fall short of established performance specifications. Subsequent, post-launch algorithm improvements and vicarious calibration are expected to help reclaim some of the performance shortfalls and close on historically attainable measurement uncertainties.

A redesigned IFA for the second VIIRS sensor manifested on the first operational NPOESS satellite has already been manufactured, with early performance estimates indicating order-of-magnitude reductions in optical cross-talk. In conjunction with improvements to the supporting algorithms and refined vicarious calibration techniques, the system is expected to have the intrinsic capability to deliver the OC/C EDR at a level of performance approaching its performance specifications and sufficient to satisfy the mission needs of the operational product stakeholders.

Fig. 6 provides an example test scene of channel-specific nLw resulting from NGST algorithm chain testing [13] using geophysically realistic test data. The results show reasonable values for the selected scene but do not include the effects of sensor artifacts such as cross-talk.

IV. SUMMARY

The advanced technology visible, infrared, and microwave sensors and supporting spacecraft and ground systems

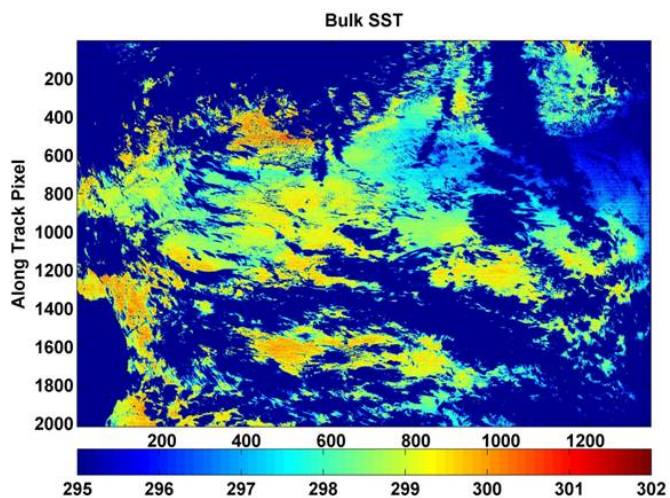


Fig. 5. Bulk SST test scene 2001213_1220 (from NGST chain testing report for VIIRS SST algorithm)

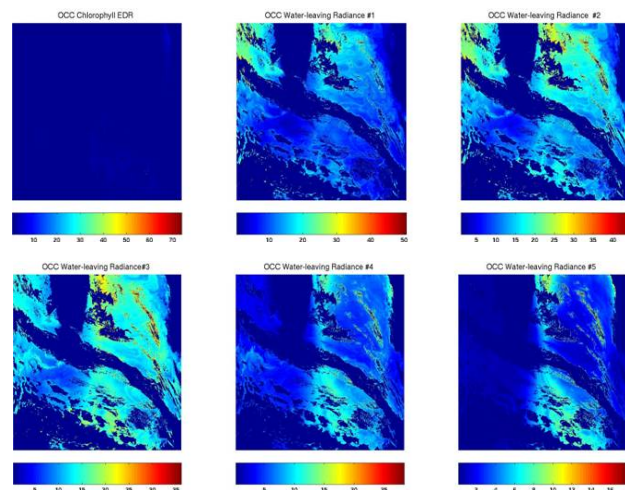


Fig. 6. OC/C test scene 26: 2003027_1315 illustrating Chlorophyll-a concentration and Ocean Color for VIIRS channels M1 through M5 (from NGST chain testing report for VIIRS OC/C algorithm)

infrastructure comprising the restructured NPOESS Program will continue to deliver earth observations with better spatial and temporal resolution and greatly improved latency when compared to operational heritage systems. Of interest to the ocean community, ocean-related EDRs continue to comprise nearly one-fourth of the user-validated products to be delivered by the system. These EDRs have driven and continue to act as drivers of the system design and acquisition strategy. NPOESS promises to transform the existing paradigm of relatively short-term space-based ocean research missions into a long-term, sustainable, operational remote sensing resource. The launch of the risk reduction NPP satellite in the Spring of 2010 will mark an important transition to availability of actual space-based data. VIIRS data from NPP will support delivery of a key ocean EDRs

(SST) to the ocean community and will permit continued improvements to delivered OC/C performance. When the MIS sensor on the NPOESS C2 satellite becomes operational, additional microwave-based EDRs will add considerably more capability for observing the ocean environment. The operational series of NPOESS satellites, beginning with C1 in early 2013, will provide continuity of ocean observations that are expected to meet or exceed the validated operational requirements of the ocean user community.

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